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Structures and Buildings

The engineering legacy of the FIFA World Cup Qatar 2022TM: Al Bayt Stadium

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In contemporary architecture, textile membranes offer a wide range of possible structural applications, especially for facades and roofs with large spans and where the reduction of self-weight plays an important role for an efficient and sustainable structural design. On 30 November 2021, the Al Bayt Stadium was inaugurated in Qatar; with its 190 000 m^2 of textile membrane it is one of the biggest architectural membrane projects in the world. An innovative new membrane material with a natural textile appearance was developed from scratch to meet the specific requirements of the project. This makes the construction of Al Bayt Stadium, shaped like the local Bedouin tents, a milestone in modern membrane architecture; this is attributable not only due to the pure size of the membrane, but also to the significant advances made in textile membrane material design and development as part of the project. Other design aspects include the large, retractable roof above the pitch, which transforms the open-air stadium into a fully enclosed and temperature-controlled multi-purpose arena within minutes. This paper presents details of the design and construction aspects of the stadium, as well as the material development conducted for the inner membrane.

Keywords: adaptive/membrane/modularity/movable/precast concrete/stadium/structural design/structure/tensile properties/textile

1. Introduction

The Al Bayt Stadium (Figure 1(a)) in the coastal city of Al Khor, 50 km north of Doha, is designed to host 60 000 spectators. It hosted the opening ceremony of the FIFA World Cup Qatar 2022, held on 20 November 2022, along with several knockout matches up to the semi-finals. In its shape and appearance, the stadium resembles a traditional Bedouin tent (Figure 1(b)); the name Al Bayt is derived from the Arabic 'bayt al sha'ar', a term used to describe the historic Bedouin tents of the nomads in Qatar and the Gulf region. Other than functioning as dwellings, larger Bedouin tents in the gulf region are used for social gatherings and celebrations; hosting the games in Al Bayt Stadium is a tribute to the Bedouin culture. The traditional tents consist of a simple timber support structure with external stay cables and a cover made of woven fabrics. Typically, distinctive features of these dwellings include both special coloured patterns in the woven fabrics of the outer shell and elaborate patterns in the fabrics of the inner lining. The outer fabrics usually have simple horizontal stripes in beige, brown or black, whereas the textiles for the inner lining have elaborately woven, graphic patterns of red, white, black and orange stripes. These traditional fabrics with 'Sadu' patterns are still used today as wall and ceiling decoration in living and reception rooms of Qatari dwellings. For the Qataris, these patterns symbolise hospitality.

The roof and facade support structure of the Al Bayt Stadium consists of a steel truss with 72 radial lattice girders that cantilever up to 62 m above the stands. The geometry of the supporting structure is developed in such a way that a large Bedouin tent is created in the contour. The roof as well as the facade is covered with a polytetrafluoroethylene (PTFE)-coated glass fibre membrane. While the 70 000 m^2 roof membrane is beige, the 30 000 m^2 facade surface is divided into black and beige stripes (Figure 2). To ensure a permanent and weather-independent use of the stadium, a convertible membrane roof of approximately 16 000 m^2 can close the opening above the pitch if required. A fluoropolymer-coated PTFE fabric was chosen for this membrane because of its excellent foldability and high translucency. This allows a reduction in the use of turf lighting for the pitch by using direct solar radiation.

Al Bayt Stadium is intended to be usable all year round. In addition to its function as a football stadium, there are several additional areas and zones within the shell structure that allow multifunctional use. In the long term, exhibition

(a)

(b)

Figure 1. (a) Exterior view of the stadium; (b) A traditional Bedouin tent

Figure 2. Construction stage of facade membrane

Figure 3. Installation of precast concrete columns

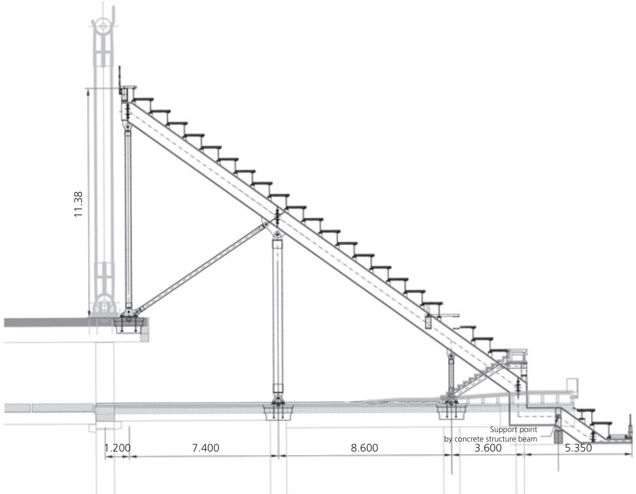


Figure 4. Section of the temporary upper tier

and sales areas, for example, will offer the possibility of later use beyond the time of the World Cup. To enable year-round use, the entire volume within the envelope structure is fully air-conditioned. This required ventilation and smoke extraction ducts in the roof structure. In addition, there are large numbers of walkways to access the technical equipment such as floodlights, loudspeakers, utility lines in the void roof. A 71 000 m^2 sub-membrane visually conceals the technical equipment and the massive ducts in the roof and creates a pleasant and uniform room enclosure.

The structure of the stadium can be divided into the following main components.

- A reinforced concrete bowl structure includes foundations, a series of escape tunnels, two player tunnels and one service tunnel, as well as a series of piers. The bowl has three tiers. The lower and middle tiers are made of reinforced concrete.
- The upper tier is made of steel with precast concrete floor plates.
- The tent roof structure comprises double-layer membrane cladding.
- A retractable inner roof can be used to close the building fully in order to protect the interior from environmental conditions such as sun and rain.

More details are provided in the following sections.

2. Concrete bowl structure

The reinforced concrete bowl structure has seven levels in total. The lower two levels are buried in the ground and provide access to the lower tier. The middle tier is accessed through levels 5 and 6. The bowl superstructure with its concourses and floor space are entirely made of precast concrete to speed up the construction process and to have an improved visual appearance of the exposed concrete elements. For this purpose, a precast fabrication facility was erected on site to reduce the transportation times and to be able to react to the site requirements at short notice. Not only the columns, beams, rakers and stairs were made of precast elements, but also the stiffening core walls were prefabricated and lifted into position. The joints between individual precast columns are formed by steel anchor shoes. The beams are directly supported on the relevant corbels of the columns, where only a thin elastomer pad was used to balance out the local tolerances. The slab elements are mainly hollow core slabs that are directly supported on the beams. An in-situ topping layer on the hollow core slabs and the beams provides the required diaphragm action for the overall bracing of the building.

To reduce the total amount of individual lifts, columns were prefabricated up to a length of 12 m – spanning several floors. Based on the high amount of prefabrication, up to 120 individual precast elements were installed per day (Figure 3).

In plan view, the bowl structure is subdivided into eight segments that are separated by expansion joints. Each segment is braced by stairwell cores and walls. Access for heavy vehicles to the stadium at level 0 and to the pitch is provided by three tunnels: the service tunnel which is 260 m long with clear heights of 6 m and widths of 9.5 m as well as two player tunnels (each 215 m long) for direct team coach access. All tunnels are interconnected with the ring road at level 0 within the bowl for deliveries and supplies.

3. Temporary upper tier

The intention was that after the FIFA World Cup Qatar 2022, the stadium capacity would be reduced to 30 000 seats. The modular design of the upper tier structure was designed to facilitate a simple, fast and safe dismantling of the upper tier in the legacy mode of the facility. In contrast to the lower bowl structure, the upper tier was designed as a modular lightweight steel structure (Figure 4). The primary steel structure of the temporary upper tier consists of raker beams located in the main building axes. The raker beams are I-sections and are supported by vertical circular steel columns at each main axis of the building. Radial diagonals between the columns in combinations with tangential bracings between the rakers provide sufficient lateral stiffness to keep the dynamic performance of the overall stand structure within acceptable limits.

To reduce the required lifting capacities during installation, but especially for dismantling, instead of regular terrace units made of concrete, a series of slender lightweight steel I-section beams span between two adjacent raker beams (Figure 5). These 'bleacher beams' provide adequate support for only a 10 cm thick precast bleacher concrete slab, which also provides bracing for the slender bleacher beams at the same time.

All assemblies between different structural elements are bolted or pinned connections, allowing for easy dismantling and possible re-assembly, if required. Similarly, all elements were designed with optimised self-weight, enabling the use of small, lightweight lifting equipment when dismantling with a crane hook capacity of maximum 2.5 t. The whole upper tier stand structure consists of eight individual segments separated by expansion joints that are above the expansion joints of the bowl structure. This created a total of three different geometries for the segments (corner, long, short). For fast installation on site complete bays consisting of the columns, diagonals, rakers and bleacher beams were pre-assembled on the ground and lifted into position by crane (Figure 6(a)). The missing elements between two pre-assemblies were then installed with smaller cranes one step at a time followed by the precast concrete bleacher slabs (Figure 6(b)).

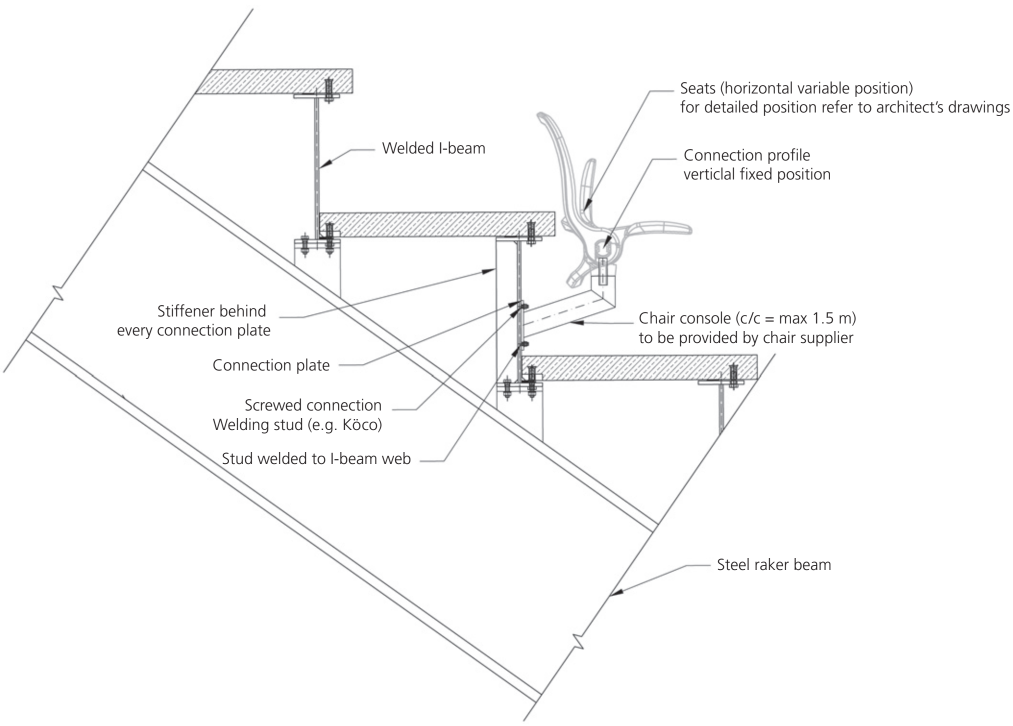


Figure 5. Bleacher beams

(a)

(b)

Figure 6. (a) Installation of individual segments of the temporary upper tier; (b) Temporary upper tier structure with precast bleacher slabs

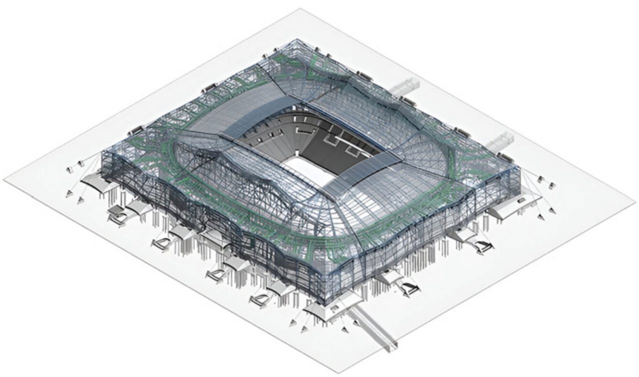


Figure 7. Building information modelling (BIM) model of Al Bayt Stadium

4. Outer roof and facade structure

The tent roof structure has plan dimensions of 311 m × 273 m. The roof has four distinctive peaks in both, the east and west portions of the double symmetrical outer roof structure. The resulting ridge lines between the peaks showcase the architectural features of a traditional Bedouin tent geometry (Figure 7).

The highest peak at the ridge line is approximately 67 m high. A total of 72 steel trusses with varying geometry form the primary structure of the outer roof (69 000 m^2 in area) and the facade structure (46 000 m^2 in area). The shape of each truss is defined to create the required tent appearance from the outside as well as have a smooth and homogeneous appearance from the inside. The steel trusses are supported at the outer perimeter on the ground directly, where they reach up vertically for the facade and then span the outer concourses. A second support adjacent to the outer perimeter of the upper tier is used to balance the large cantilever of up to 62 m above the stands (Figure 8).

A series of purlins span between the individual trusses; the diagonally arranged bracing tubes provide sufficient lateral stiffness for horizontal loads (Figure 9). Expansion joints divide the double symmetrical outer roof structure in eight segments. These are aligned with the ones in the concrete bowl structure.

The primary trusses and the purlins are used directly to fix the membrane cladding. The number of trusses and the spacing of the purlins have been optimised during the design process in consideration of the structural membrane design and performance. The structural principle behind the roof and facade structures is shown in Figure 10. Each truss is supported by a steel column on top of the concrete bowl as well as at the outer edge on the ground. Vertical forces – as, for example, due to gravity loads or wind pressure – acting downwards on the radial trusses result in a compressive force on the bowl and a tensile force at the ground support. The overall bending moment due to the force eccentricity is balanced by a pair of vertical forces (shown in red in Figure 10). Horizontal forces acting on the facade are transferred to the outer support. The resulting global bending moment is balanced by a pair of vertical forces (shown in green in Figure 10).

The outer roof membrane cladding comprised a 70 000 m^2 beige coloured PTFE-coated glass fibre membrane with breaking strengths of 175 kN/m and 140 kN/m in the warp and fill directions, respectively (Bögle *et al.*, 2011; Goldack *et al.*, 2014; Paech and Stockhusen, 2018). The material strength as well as the strength of the welds were tested according to the procedure described within DIN EN ISO 1421:2017-03 (DIN, 2017). The tests were carried out at room temperature as well as at 70°C. The membrane design itself was carried out according to the guidelines of the *European Design Guide for Surface Tensile Structures* (Mollaert and Forster, 2004). The membrane is directly clamped to the upper chords of the steel trusses and the associated purlins. The pre-tension and geometry of the individual panels has been defined in such a way that the overall traditional tent appearance is preserved. To

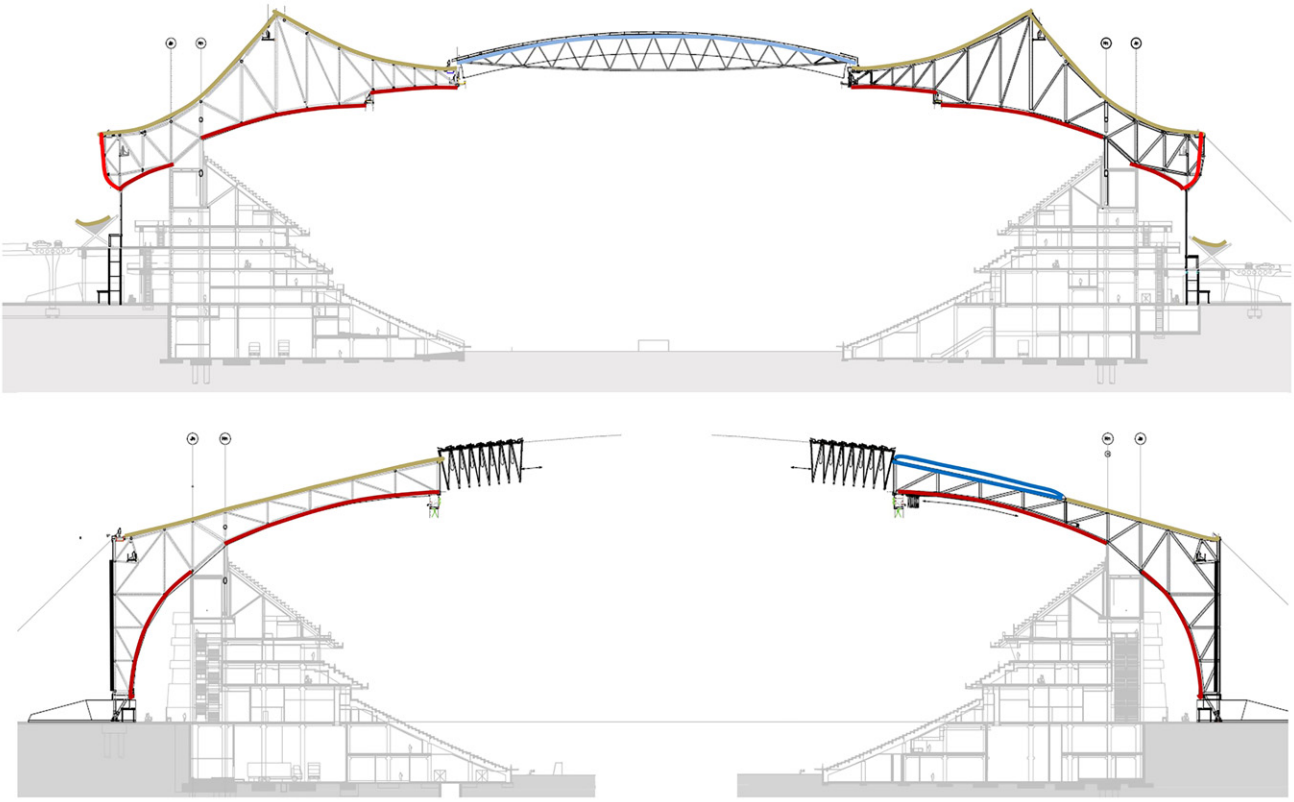


Figure 8. Section in east–west direction (top) and north–south direction (bottom)

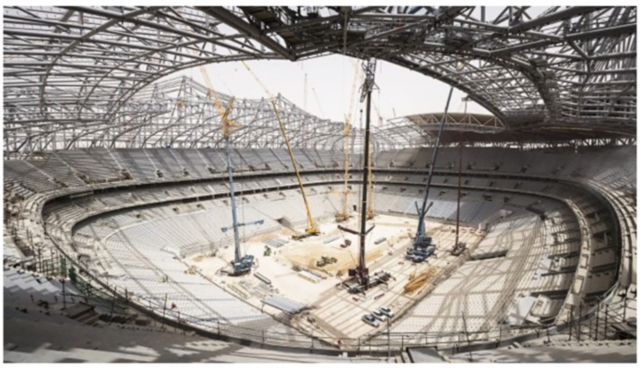


Figure 9. Roof steel at erection stage

identify the compensation values that are required for the cutting patterns, biaxial compensation tests were performed. The test regime and duration took into account, on the one hand, the required stress ratios under pre-stress and, on the other hand, the expected stress variation during the lifetime of the structure. For the 30 000 m^2 facade a black and beige PTFE-coated glass fibre membrane was used to reflect the traditional appearance of a tent. Individual membrane panels of up to 1200 m^2 in size were prefabricated in the workshop, lifted into position and installed on site (Figure 11).

In most stadia around the world, the outer roof provides some shading of the pitch, so that a large amount of light is required for turf growth (Göppert *et al.*, 2011). Since solar radiation is sufficiently available in Qatar, a smart solution was found to reduce the need for growing lights by using an ethylene tetrafluoroethylene (ETFE) roof with a retractable lower blind membrane. The south segmentern of the outer roof structure above the stand was clad with a transparent ETFE, so that even in winter a high proportion of natural radiation reaches the pitch. In the summer months, the radiation must be reduced and therefore a retractable lower blind was designed so that complete shading can be provided if required. Compared to the textile membrane, ETFE has a reduced strength and consequently an additional set of radial purlins had to be installed to provide extra support for the ETFE.

5. Retractable inner roof

One highlight of the Al Bayt Stadium is without doubt the 16 000 m^2 deployable and retractable inner roof above the field of play, which transforms the open-air stadium into a fully enclosed multipurpose arena within 20 minutes. The ground plan dimensions of the inner roof are approximately 95 m in the east–west direction and 160 m in the north–south direction. When the inner roof is closed, the bowl and the pitch are protected from weather conditions and are covered in full shade – a key requirement for a sustainable cooling strategy. With the

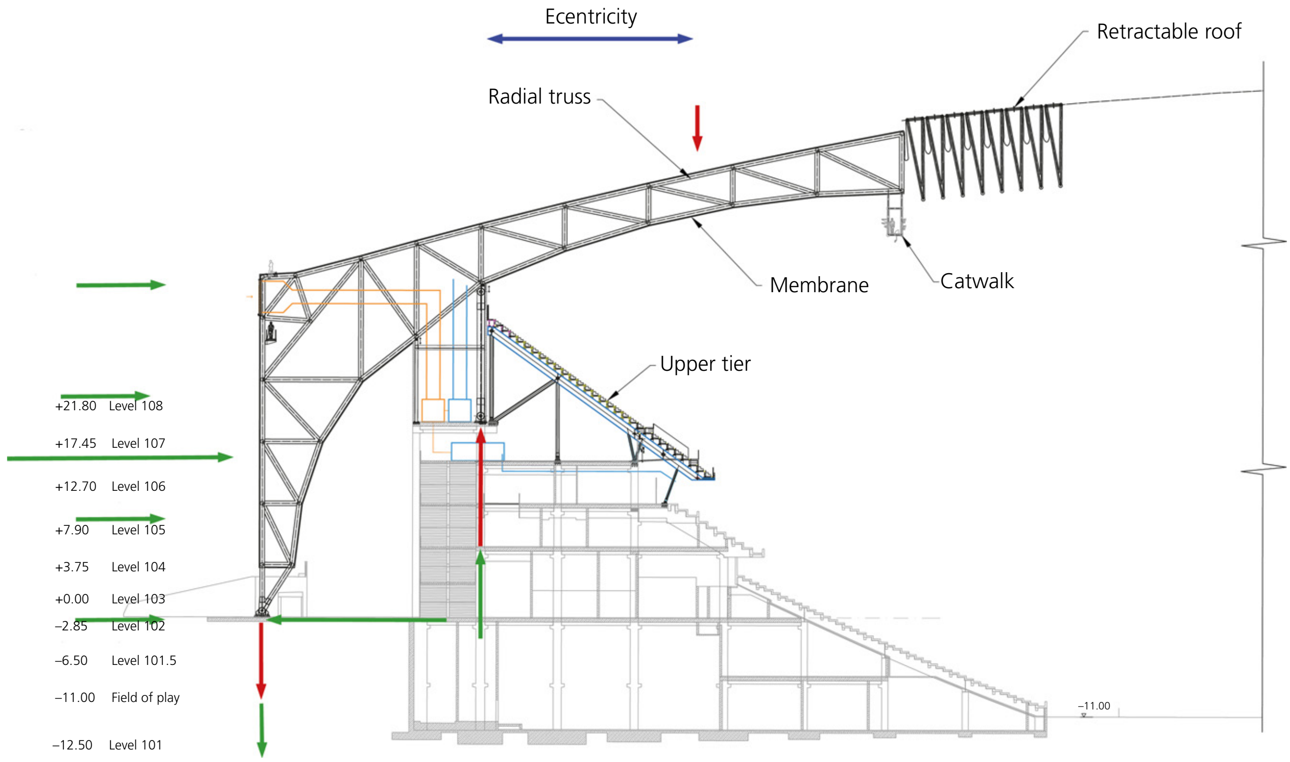


Figure 10. Structural concept of the roof and facade

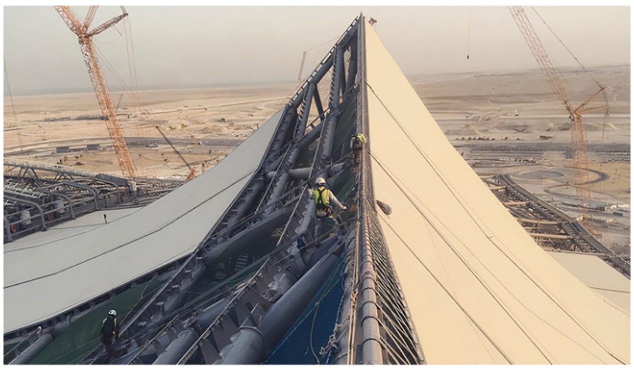


Figure 11. Installation of polytetrafluoroethylene (PTFE)–glass roof membrane

Figure 12. Retractable roof truss assembly stage

retractable inner roof, the temperatures on the stands as well as on the pitch can be reduced to ensure sufficient comfort for spectators and players even in summer with outside temperatures of up to 50°C. The inner roof therefore reduces the required energy consumption for air-conditioning significantly.

The retractable roof is double symmetrical and consists of two individual segments. Each segment consists of nine bow-shaped steel trusses that span 95 m above the field of play in the east–west direction. The trusses are single-span trusses that are supported on the outer roof structure to prevent global forces from the individual segments of the outer roof structure from imposing additional loads on these lightweight moving trusses. The trusses are shaped according to their moment diagram, forming a three-chord truss with diagonals. The maximum height of the truss is 8 m in the centre. Two upper chords are spaced 1.7 m c/c for the middle trusses and 2.2 m c/c for the end trusses. The double upper chords are braced, forming a horizontal truss to prevent instabilities of the upper chord under compression. In their deployed condition, the trusses are spaced approximately 10 m c/c. The trusses were assembled on the ground (Figure 12) and then lifted into

Figure 13. Driving carriage with rail structure of retractable roof during commissioning

Figure 14. Moving trusses with spreader arms before membrane installation

position from outside the stadium using a crawler crane of 1250 t capacity, which is one of the largest cranes in the world.

Membrane panels (cladding elements) made of a fluoropolymer-coated PTFE were installed between the steel trusses' membrane. Since the membranes were fixed to the bow-shaped upper chords, each panel had a double curvature to transfer the relevant loading from wind, rain and sand in an efficient manner. The individual trusses are supported by active driven carriages (Figure 13) on a rail that is directly supported on the outer roof structure. Each carriage is equipped with an active rack and pinion drive so that individual trusses can be moved along the rail. The drives at the carriages at both ends of each truss are synchronised by the control system so that a parallel movement is always achieved.

The pre-stressed membrane panels (when fully deployed) between the trusses transfer all occuring loads (wind loads, sand loads, etc.) by way of membrane action to their supports

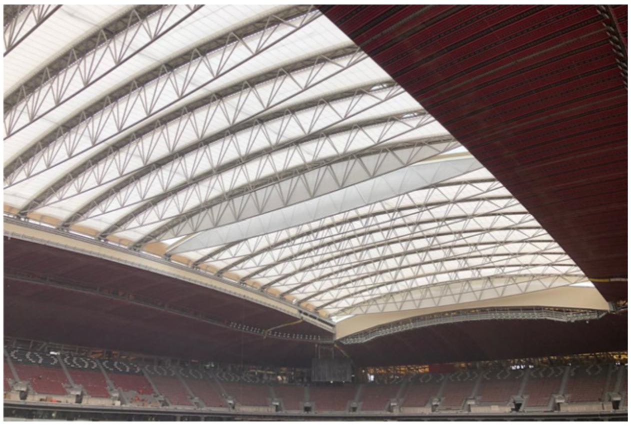


Figure 15. Retractable roof in closed condition

at the trusses. Consequently, the membrane imposes significant horizontal loads to each truss. To reduce the resulting bending moments in the trusses and to achieve an optimised design, four spreader arms were installed between every two adjacent trusses to reduce the resulting forces. The spreader arms themselves are equipped with three hinges allowing them to fold during the retraction process. All four spreader arms per bay are linked to each other in the middle by a ridge cable. When fully deployed, the ridge cable is fixed at the ends to restrain the spreader arms in position (Figure 14).

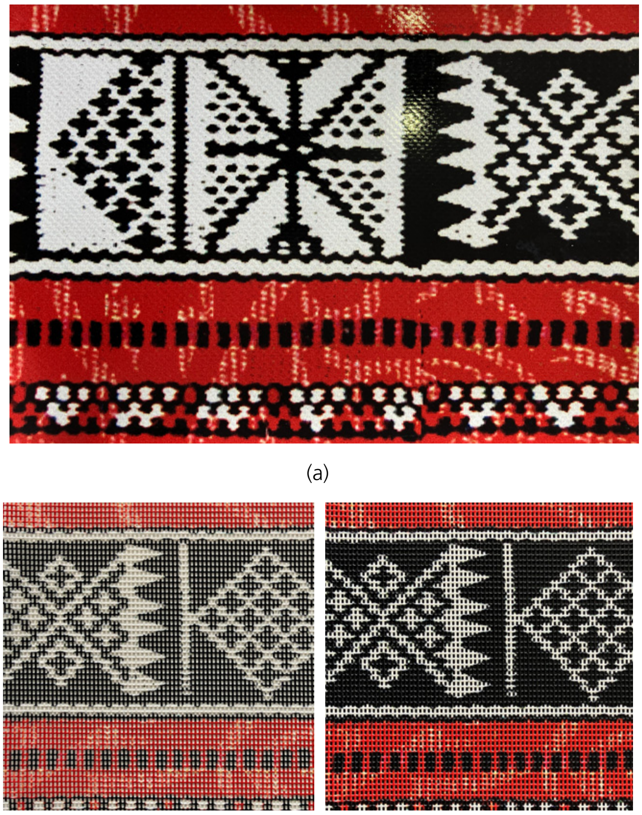
During the retraction process, the restraint of the ridge cable is released and the first steel truss is moved by the carriages towards the second truss. The membrane becomes slack and folds downwards due to its self-weight. When the first truss reaches the second, both trusses move together towards the third truss and so on. When fully retracted, the operable roof is reduced to approximately 20.5 m × 95 m for the north and the south segments respectively. This corresponds to approximately 20% of the fully unfolded geometry of the operable roof in plan view (Figure 15).

A specific feature of the retractable roof at Al Bayt is that both roof segments can be retracted and parked in the northern part of the opening above the field of play. This is an important aspect to improve the amount of solar radiation required for grass growth the turf in the winter months when the sun is relatively low (Göppert *et al.*, 2013).

6. Innovative material development

6.1 Aesthetics

The fabric panels with the traditional Sadu pattern have a red base colour, and the geometric patterns are woven in white and black and partly in orange. The patterns run and repeat in the warp direction of the fabric. On the bottom side of the roof structure, the characteristic stripes were to run radially to



(a)

(b)

Figure 16. (a) Printed polyvinyl chloride (PVC) polyester membrane; (b) Printed PVC polyester mesh membrane with different background colours (close-up)

the pitch. An aesthetically important aspect for the design is the appearance of a textile based on traditional fabrics.

6.2 Required material properties

The extreme climatic conditions in Qatar with maximum air temperatures of over 50°C, which also occur seasonally in combination with high humidity, were a major challenge in terms of durability, but also in terms of the required static properties of a textile membrane. Since the material and weld seam strength of polyvinyl chloride (PVC)-coated polyester membranes decreases at elevated temperatures, this had to be considered in the appropriate choice of material and also in the material development (Cremers, 2015; Krüger, 2009). According to a static calculation for the relevant wind loads and the given steel structure, the material strength at 23°C should be at least 84 kN/m in the warp direction and 70 kN/m in the weft direction. In addition, the locally applicable regulations define very strict requirements for the fire behaviour of building materials that may be used in a place of assembly. The membrane should at least comply with fire class B-s2-d0 – limited contribution to fire BS EN 13501-1:2018 (BSI, 2018). Furthermore, the membrane should meet appropriate acoustic requirements to keep the reverberation time within the

Figure 17. Magnified section through polyester yarns with PVC coating

stadium, especially for safety instructions, within appropriate limits.

6.3 Material study

As described above, various requirements for the membrane material and its appearance were defined. Several material types were investigated and compared in a detailed investigation. Glass/PTFE fabrics were excluded for the Sadu pattern due to their limited colour selection as well as limited printability. In contrast, a solid PVC-coated polyester membrane meets the mechanical requirements and can be printed with appropriate patterns. However, it offers no textile surface structure or optics. In addition, a sealing lacquer is required to ensure certain durability of the printing. This makes the membrane appear very glossy, which takes the final product even further away from the appearance of a textile (Figure 16(a)). An acoustic study also revealed that the required reverberation time with a solid submembrane would have to be classified as critical.

A printed PVC-coated polyester mesh membrane with openings of approximately 2 mm in size has a textile appearance, even if the pattern does not match the mesh structure. The coloured print on a mesh membrane must also be protected with a sealing lacquer with a gloss effect, as described above. Acoustic testing showed that the reverberation time is improved compared to a solid membrane, but in some parts of the roof additional acoustic insulation would have been required on the back of the membrane. The visual appearance of the mesh membrane is influenced on the one hand by the light conditions above the lower membrane, but also by a

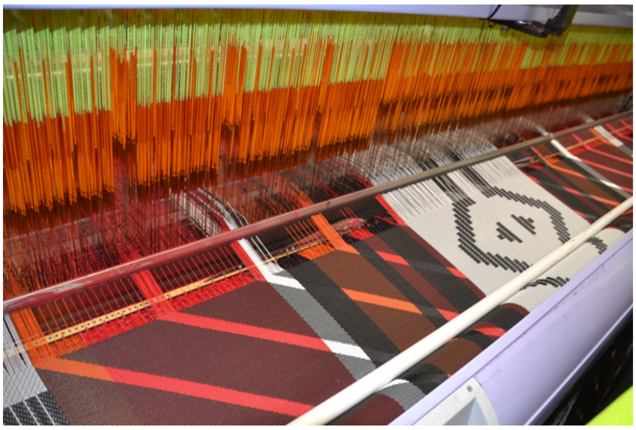


Figure 18. Weaving of Sadu pattern using jacquard methodology

Figure 19. Close-up photograph of the jacquard woven membrane

partially necessary acoustic insulation, so that a highly heterogeneous appearance was to be expected. Figure 16(b) shows an example of the appearance of the membrane on a light and on a dark background.

To ultimately achieve a woven and textile appearance, another alternative was developed in collaboration with the membrane supplier: a specially woven membrane made of colour-coated single threads with a striking textile character. In contrast to the printed alternatives, the coloured, patterned, woven membrane promised – high durability and colour stability. The material and surface properties also gave the membrane good acoustic properties, so that the reverberation time in the stadium could be maintained without further measures. Initially, simple and small-format prototypes with different patterns were produced in order to study the basic feasibility, quality and appearance conceptually and to be able to develop the product further accordingly.

6.4 Manufacturing process and tissue structure of the lower membrane

The basis for the patterned lower membrane is formed by polyester threads with a sheathing PVC extrusion. The PVC with appropriate antibacterial and fire-retardant additives, as it is the case with a commonly used PVC/polyester membrane, serves to protect the polyester thread from ultraviolet radiation (Figure 17). Four different colours of the PVC-coated threads were used for the weaving process with the Sadu patterning.

6.5 Weaving technique – jacquard pattern

Jacquard patterning is a joining technique that offered an important extension in the design of woven and knitted fabrics when it was invented in 1805 (Paech, 2016, 2019). Joseph-Marie Jacquard invented a loom that made it possible to control the position of each warp thread. For the first time, it was possible to produce industrially woven fabrics with patterns that could be repeated as often as desired, even complex ones. At the same time, these looms, known as jacquard looms, were the first machines that could produce fabric patterns using punched cards. This made it possible to produce fabrics with more complicated patterns. This weaving technique is still widely used today in the textile industry to weave patterned fabrics, although the punched cards used in the past have been replaced by digital control. The application of this technique for the Al Bayt Stadium described below is so far unique in the construction sector (SBP, 2019).

In this technique, different coloured warp threads are first rolled onto the so-called warp carrier. The colour arrangement of the warp threads is determined depending on the subsequent pattern. The weft thread is always black in the selected pattern. With the digital jacquard control, before the weft thread is pulled, the warp threads are set according to the pattern, so that a predetermined number of warp threads are skipped during weaving. Depending on the pattern, up to seven warp threads are skipped. This technique results in the reverse fabric pattern, upper face on the underside of the fabric (Figure 18). In order to stabilise the loose fabric in its unity, while also considering the cutting and trimming that is anticipated afterwards, the warp and weft threads are subsequently heat-set without completely fusing the fabric structure.

6.6 Material properties of the jacquard woven membrane and tests

The patterning has a significant influence on the material properties of the woven membrane. Owing to the desired colour gradient, not every warp thread is bound to every weft thread, but individual warp threads can skip up to seven weft threads, as mentioned above. In these areas, the textile membrane has a locally increased stiffness in the warp direction, as the warp thread runs almost straight here and is less deflected in its running direction (Figure 19).

For the structural analysis and design of the membrane, an anisotropic linear elastic approximation of the material properties was considered. To capture the variation of stiffness within the pattern, the system was analysed using an upper and lower range of stiffness. All of the generated results of this engineering approach were used for the relevant design verifications.

Not only the stiffness is influenced by the different patterning, but also the tensile strength of the material (Göppert and Paech, 2015). In addition, due to the different stiffness distribution, there are stress redistributions within the fabric, which must be considered in the structural design. Uniaxial tensile tests as well as biaxial tests in the warp and weft directions were carried out at eight different locations of the continuous pattern to quantify these influences. In the tests, the tensile strength was determined, as well as the corresponding elongation stiffness and stiffness ratios. The minimum tensile strength determined in the tests at room temperature as a function of the pattern for 10 cm wide samples was approximately 84 kN/m in the warp direction and 70 kN/m in the weft direction. The corresponding mechanical behaviour of weld seams was also tested. The weld strength was approximately 90% of the material strength at room temperature and fell to approximately 76% of the material strength at 70°C. For the structural design and verification, the worst-case stress results of the stiffness variation analysis were compared with the minimum material strength achieved for all the different areas of the pattern. A global safety factor of 4.5 was assumed for the design. This factor takes into account possible aging, temperature effects, biaxial actions and material safety, and includes the required partial safety factors of the loads. In addition, fire behaviour tests were carried out. These confirmed that the specially woven membrane can be classified as B-s2-D0 according to BS EN 13501-1:2018 (BSI, 2018).

6.7 Assembly and installation

The individual membrane panels are attached linearly to the bottom chords of the radial trusses using aluminium keder strips. The maximum distance between the radial girders is approximately 16 m. To reduce the membrane stresses, the membrane is also held against suction loads at the tangential roof purlins. Splices of the membrane are only provided in the radial axes due to the required continuous arrangement of the Sadu pattern. The individual panels of the lower membrane, which are manufactured in the fabrication shop measure up to 1012 m^2. At the construction site, the individual segments are lifted and pre-stressed with 2 kN/m in warp and weft directions.

7. Summary and outlook

Different types of lightweight membranes and foils have been used in the design of the Al Bayt Stadium. The material choice reflected the different demands for the cladding material and the envelope. Special attention was paid to the development of the membrane material for the inner membrane. The membrane material had to meet particularly high requirements in terms of appearance and, due to the extreme climatic conditions, durability. As it is also the sub-membrane of a stadium roof, various aspects such as fire safety requirements and acoustic properties had to be considered. These special requirements could not be met by an existing material, which is why a new material had to be developed from scratch for the Al Bayt Stadium. For this purpose, various manufacturing processes were run through, different materials were tested and finally the developed material was made ready for use. This time-consuming process was only possible with a well-coordinated team in which everyone could contribute their individual expertise. The interdisciplinary team of engineers, architects and manufacturer entrusted with the task was only able to fulfil all the necessary requirements for the fabric optimally through this collaborative working method. In the future, there will be even more diverse applications in roof and facade construction, for which this innovative material is ideally suited because of its properties.

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